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Modelling a C-Band Space Surveillance Radar using Systems Tool Kit

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ABSTRACT

A model of the AN/FPQ-14 C-Band radar was developed using Analytical Graphics, Inc. (AGI) STK software to support studies investigating the operational performance of the system for surveillance of Space and the contribution it could make to the Space situational awareness mission. STK scenarios were developed to assess the detection performance of the radar model against a satellite target with a given orbital altitude, radar cross section (RCS) and minimum signal to noise ratio (SNR) required for detection. These results were compared to those obtained by evaluating the radar range equation. A comparison was also made on the effects of refraction using the effective radius method and International Telecommincations Union (ITU) model.

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Executive Summary

The US Space Surveillance Network (SSN) is a collection of sensors dispersed around the world for surveillance of Space. These sensors are used to detect, track, identify and characterise objects in Space such as payloads, rocket bodies and debris to provide Space situational awareness information.

The AN/FPQ-14 is a conventional (dish) radar used for surveillance of Space. This radar operates in the C-Band (5.4 to 5.9 GHz) and can provide very accurate tracking information on objects in Space, however it can only track objects within a very narrow beam and requires cueing to the target.

In order to support studies investigating the operational performance of the AN/FPQ-14 radar for Space surveillance and assess the contribution it can make to the Space situational awareness mission, a model of the radar was developed using Analytical Graphics, Inc. (AGI) Systems Tool Kit (STK) software.

STK formerly known as Satellite Tool Kit, is a computer software suite for modelling, analysing and visualising Space, defence and intelligence systems. The software can be used to develop high fidelity models and simulations of complex systems such as aircraft and satellites as well their sensors and communications. It includes an add-in module specifically for detailed analysis and visualisation of radar systems, STK/Radar, which has been extensively used in this work.

The radar is modelled as an object in STK by defining basic parameters including: mode of operation, frequency, peak power, antenna setup, system temperature and other gains and losses. Fidelity of the model is increased by considering additional advanced settings available in STK/Radar. These include modelling of pulse integration modes required to simulate tracking of targets. The effects of refraction are also taken into consideration.

A STK scenario was created to assess the detection performance of the radar model against a satellite target with a given orbital altitude, radar cross section (RCS) value and minimum signal to noise ratio (SNR) required for detection. STK computes 'access' (i.e. visibility from one object to another based on constraints placed on them in the

scenario) from the radar to the target and outputs the azimuth, elevation and range when it is being tracked.

The STK detection performance results for the radar were compared to those obtained from a simple analysis that determined the detection range of objects with a given radar cross section (RCS) using the estimated operating characteristics of the radar input into the radar range equation which has been reported in previous work. A comparison was also made on the effects of refraction using the effective radius method and International Telecommunications Union (ITU) model.

The results showed that for a given minimum SNR required for detection of 15 dB, which based on previous analysis appeared to closely match what was known about the operating performance of the radar, orbital objects with a 1 m^2 RCS (considered to be representative of a payload) can be detected out to the radar horizon at an orbital altitude up to about 500 km, whereas detection of much larger objects, e.g. boosters with a 40 m^2 RCS, are horizon limited regardless of the orbital altitude for objects in LEO. Detection of small payload size objects and smaller ones (less than 0.1 m^2) will be limited by the performance of the radar and debris with an average RCS less than or equal to 0.01 m^2 are unlikely to be detected at the higher LEO altitudes (above about 1200 km).

Contents

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Acronyms and Abbreviations

AGI	Analytical Graphics, Inc.
CFAR	Constant False Alarm Rate
CW	Continuous Wave
ITU	International Telecommunications Union
LEO	Low Earth Orbit
LOS	Line of Sight
PRF	Pulse Repetition Frequency
PSD	Power Spectral Density
RCS	Radar Cross Section
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SCF	Satellite Control Facility
SNR	Signal-to-Noise Ratio
SSA	Space Situational Awareness
SSN	Space Surveillance Network
STK	Systems Tool Kit

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1. Introduction

The US Space Surveillance Network (SSN) is a collection of sensors dispersed around the world for surveillance of Space. These sensors are used to detect, track, identify and characterise objects in Space such as payloads, rocket bodies and debris to provide Space situational awareness information.

One such sensor in the SSN is the AN/FPQ-14 C-Band radar. This is a large parabolic dish radar which can provide very accurate tracking information on objects in Space. The radar is currently located in Antigua as part of the US Eastern Range, however, it has been proposed that it should be relocated to North West Cape, Western Australia in order to increase the coverage of the SSN over the southern hemisphere which is currently quite limited.

Limited information was known about the operational characteristics of this radar, so a model was developed using Analytical Graphics, Inc. (AGI) System Tool Kit (STK) software in order to support studies investigating the performance of the radar for Space surveillance and assess the contribution it can make to the Space situational awareness (SSA) mission.

This report documents the approach used to model the AN/FPQ-14 radar using the STK software including the development of a scenario to assess the detection performance against a satellite target with a given orbital altitude, radar cross section (RCS) value and minimum signal to noise ratio (SNR) required for detection with the radar located in North West Cape, Western Australia.

The report consists of the following sections:

- an overview of the AN/FPQ-14 radar including a description of the known technical specifications;
- an overview of STK, including its capabilities as a modelling, simulation and visualisation tool, and the development of the radar model;
- the STK scenario developed to assess the operational performance of the radar; and
- a discussion of how the STK results were validated, including a comparison against the radar range equation and analysis of the effects of refraction.

This report is intended to supplement and expand on the modelling and simulation of the radar contributing to the assessment of its operational performance described in previous work [1].

2. Overview of the Radar

2.1 Background

The AN/FPQ-14 is a conventional (dish) radar used for surveillance of Space. The radar is currently located at the US Air Station on Antigua (17°5′N 61°48′W) as part of the US Eastern Range. The radar, shown in Figure 1, has a dish antenna consisting of a circular reflector with a parabolic profile. This shape generates a narrow, axially symmetric beam. The reflector can be steered in two angular coordinates to point the beam towards the target [1].

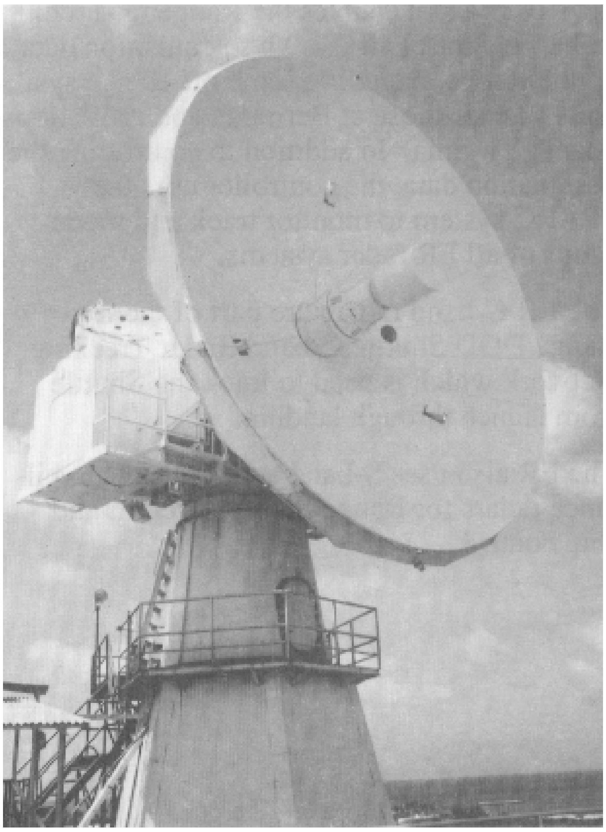

Figure 1: The AN/FPQ-14 radar located at Antigua

The radar operates in the C-Band (5.4 to 5.9 GHz) and can provide very accurate tracking information on objects in Space; however, it has limited search capability given that it can only track objects within a very narrow beam. It is capable of tracking using either beacon (transponder) or skin (echo) signals in both vertical and circular polarization modes.

The primary mission of the radar for Space surveillance is to contribute to catalogue maintenance of objects in Low Earth Orbit (LEO), i.e. objects already in orbit such as satellites and debris that have an orbital element set maintained in the satellite catalogue.

The radar may also be able to contribute to the tracking of new objects and Space launches, however, cueing to the target would be required. The radar has on-axis tracking capabilities

which allow the antenna to be computer driven using data from a predetermined orbit generator program [2].

2.2 Technical Specifications

Given limited information was available regarding this radar, and in particular its operational performance, a model of the radar was developed using information available in the public domain and from discussions with radar specialists. This model contributed to assessments of the operational performance if the radar were to be relocated to North West Cape, Western Australia. Additional information subsequently sourced from a preliminary technical manual [3], which included details on the operational specification, was used to refine the set of parameters reported in the original work [1].

The unclassified technical specifications of the radar are presented in Table 1. These were used as the basis for defining the radar model developed in STK. The radar uses a three megawatt coherent transmitter with a 29 foot, 53 dB gain antenna and has a 0.38° beamwidth.

Table 1: Antigua AN/FPQ-14 radar specification

Wavelength Band	C Band (5.4 to 5.9 GHz)
Peak Output Power	2.5 MW
Pulse Repetition Rates	160, 320 and 640 pps
Beam Width	0.38°
Antenna Size	29 ft
Antenna Gain	53 dB
Max Range	32000 NM
Range Accuracy	18 ft
Angle Accuracy	0.07 – 0.10 mrad
Slewing Rates	80000 yds/sec

The estimated operating characteristics used in the modelling are presented in Table 2. These replicate the parameters described in previous work [1] to estimate detection ranges when applying the radar range equation, which was used for comparison of the STK results. Further details are provided in this report including a more comprehensive description of assessing the operational performance of the radar.

Table 2: AN/FPQ-14 Estimated Operating Parameters

Parameter	Estimated Value
Nominal Frequency	5.65 GHz (mid range)
Peak Transmitted Power	2.5 MW
Pulse Repetition Rates	160, 320 and 640 pps
Pulse Widths	1 and 12.5 μs
Beam Width	0.38°
Antenna Gain	53 dB
Noise Temperature	578.60 K[1]
System Internal Losses	4 dB
System Altitude	10 m
Number of Pulses Integrated	40
Integration SNR	15 dB

3. Modelling the Radar

3.1 STK Overview

Systems Tool Kit (STK), formerly known as Satellite Tool Kit, is a commercial off the shelf computer software package developed by Analytical Graphics, Inc. (AGI) for modelling, analysing and visualising Space, defence and intelligence systems [4]. The software can be used to develop high fidelity models and simulations of complex systems such as aircraft and satellites as well as their sensors and communications.

STK was originally developed to solve problems involving Earth-orbiting satellites, although it has since been expanded to cover air, sea and land environments as well as Space. At the core of STK is a geometry engine that is designed to determine the time-dynamic position and attitude of assets, determining dynamic spatial relationships among all of the objects under consideration, including the quality of those relationships or accesses given a number of complex, simultaneous constraining conditions [5].

STK is a modular product allowing additional functionality to be integrated into the standard product. The basic edition of STK, which forms the core of the product and is freely available,

[1] The system noise temperature for this type of radar can be estimated as the ambient temperature multiplied by the receiver noise figure. A typical noise figure of 3 dB at 290 K is assumed.

allows the user to model objects and their sensors, compute access[2] between them and/or fixed points on the surface of the Earth and import data from the satellite catalogue.

The professional edition adds features such as high fidelity trajectories, more complex system modelling and 3D analysis and visualisation to the product. The graphical user interface of STK 9 Professional is shown in Figure 2. A variety of specialised add-in modules are also available for the product. These are not described here and more information can be found on the AGI website, http://www.agi.com.

The STK Professional Edition (Version 9.2) was used in this analysis in conjunction with the STK/Radar module, which is described in the next section. None of the other modules available with STK were utilised.

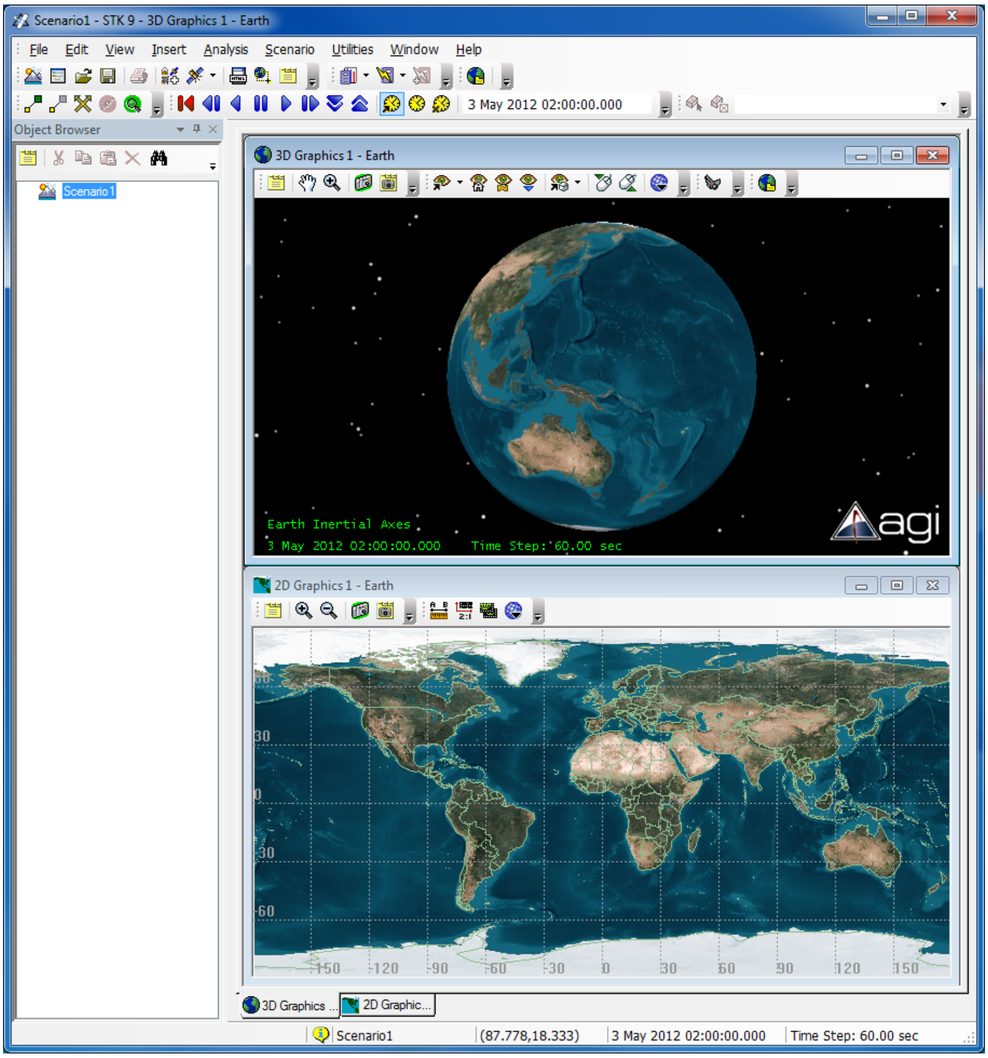

Figure 2: STK 9 Professional default graphical user interface

[2] The term 'access' refers to visibility from one object to another based on the constraints placed on them in the STK scenario.

3.2 STK/Radar Module

STK/Radar is an add-in analysis module in STK for simulating ground, Space and airborne radar systems [6]. It enables STK to perform detailed analysis and visualisation of radar systems.

Some of the key capabilities of the STK/Radar module are:

- Simulation of both monostatic and bistatic radar systems.
- Modelling of system characteristics (e.g. transmitter power, frequency, antenna size) and gain/loss factors.
- Support for operations in Synthetic Aperture Radar and/or Search/Track modes.
- Modelling of RCS for targets. Targets can be assigned a constant RCS value or multiple frequency dependent RCS. This enables STK to calculate and display access between the radar and a target.
- Several different antenna types are included or the user can import their own antenna pattern.

3.3 Radar Model

A detailed radar system model can be developed for the AN/FPQ-14 C-Band radar using the STK/Radar module. This section describes the modelling of the radar as an object within an STK scenario and is based on the information contained within the relevant sections of the STK 9.2 Desktop Application Help [7], additional technical notes supplied by AGI and other sources. The parameters defining the STK model of the AN/FPQ-14 C-Band radar can be found in Appendix A. These have been translated from the estimated operating parameters of the radar provided in Table 1 with some assumptions made based on discussions with radar experts.

STK/Radar is a complex module which can model radar systems with a high level of fidelity. A high level overview of the radar system modelling options available to the user is presented in Figure 3. For the model described in this report the aspects under consideration are the basic system definition, search/track modes, refraction and constraints. Synthetic aperture radar (SAR) and jammers can be modelled but are not applicable in this case. Polarisation is represented in STK as elliptical polarisation modelled on the Poincaré sphere but is not taken into consideration since the RCS assigned to targets in the scenario is not polarisation dependent.

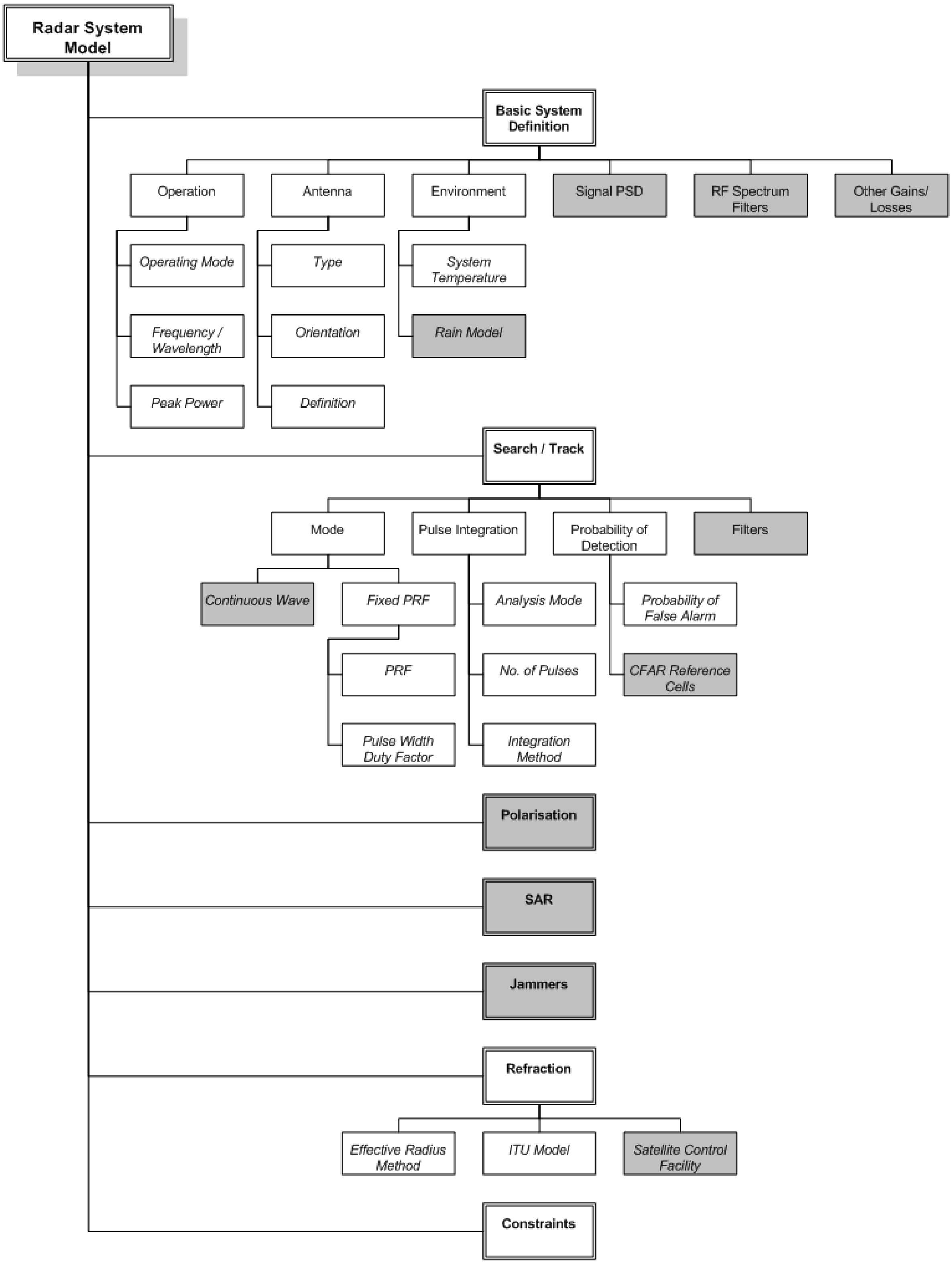

Figure 3: High level overview of the radar system modelling options in STK/Radar. Greyed out cells are not considered in the model but are available in STK/Radar. Not all parameters are shown.

3.3.1 Basic System Definition

The basic system definition settings define the general characteristics of the radar system being modelled including the mode of operation, frequency, peak power, antenna options, system temperature, rain outages and other gains and losses.

Radar Operation

The radar operating parameters set the mode of operation of the radar (monostatic or bistatic) and the frequency and peak power of the system. The AN/FPQ-14 operates in monostatic mode with a common antenna for both transmitting and receiving. The estimated operating characteristics (Table 1) are used to set the frequency and peak power values.

Antenna Properties

A parabolic antenna type is used to represent the AN/FPQ-14 C-Band radar. STK uses an analytical model of uniformly illuminated circular aperture dish to model this antenna type. The parabolic antenna is defined by specifying either the diameter, beamwidth or gain of the system with the other two parameters derived by equations (1) and (2) [8]. Equation (1) shows that the gain is also dependent on the antenna efficiency. For this antenna type the efficiency is typically between 50 and 75%.

The gain of a parabolic antenna can be defined as:

$$G_{dB} = 10\log\eta\left(\frac{\pi D}{\lambda}\right)^2 \tag{1}$$

Where:
D - Antenna diameter (size)
λ - Wavelength
η - Antenna efficiency

The 3dB beamwidth of this antenna is given by:

$$\theta_{3dB} = \frac{k\lambda}{D} \tag{2}$$

Here k is a factor that varies depending on the chosen illumination law. For uniform illumination, $k = 58.5°$ when applying equation (2).

Environmental Factors

Environmental factors associated with the radar that can be modelled include the system temperature, rain loss and refraction. Refraction is enabled for the radar analysis and discussed in §3.3.3 in more detail. A rain loss model can be selected, however, given that the modelled reduction in detection range has been shown to be quite small, less than 10% [9], it has not been considered here.

The system temperature can be defined as a constant value or calculated based on the parameters listed in Table 7 of Appendix A.

Other Gains and Losses

Post transmit gains and losses that affect performance but are not defined using the built-in analytical models can be specified for the radar; however, due to the lack of available information no additional post transmit gains or losses were defined.

3.3.2 Search/Track Mode

The Search/Track mode is used to model the detection and tracking of targets by the radar. STK can model continuous wave and fixed pulse repetition frequency (PRF) radars. The Search/Track parameter settings in STK are defined to approximate the search and track settings for the AN/FPQ-14 C-Band radar. This is not a true representation for this radar, which implements complex pulse integration schemes which would be difficult, if not impossible, to model in STK.

Search/Track Parameters

The AN/FPQ-14 is a fixed PRF radar which will continuously emit pulses (at the rate defined by the PRF) in order to form an echo from a target. The radar can also track targets using transponder signals, however, this mode is not considered here.

Fixed PRF radars in STK are defined by specifying one of the PRF, unambiguous range or unambiguous velocity. This value is used to derive the values for the other two parameters using equations (3) and (4) [10]. Similarly the pulse width or duty factor of the radar is defined with the other derived automatically, where the duty factor is equal to the pulse repetition frequency multiplied by the pulse width.

The unambiguous range is given by:

$$R_U = \frac{c}{2 \cdot PRF} \tag{3}$$

Where $c \approx 3\times10^8$ (speed of light)

The unambiguous velocity is given by:

$$v_U = \frac{c \cdot PRF}{4f} \qquad (4)$$

Where f is the nominal frequency of the radar

Probability of Detection

STK/Radar implements a swerling detection model. A constant false alarm rate (CFAR) receiver adjusts the detection threshold based on the noise in reference 'cells' around the cell being examined for the presence of a target. The probability of detection[3] is a function of the per pulse SNR, the number of pulses integrated, the probability of false alarm and the RCS fluctuation type (taken from the target RCS properties). For CFAR radar, the probability of detection is also a function of the number of reference cells [7].

Pulse Integration Mode

Pulse integration settings are defined for search/track radars. For fixed PRF radar, the integration analysis can be based on the desired signal-to-noise ratio (Goal SNR) or a fixed number of pulses (Fixed Pulse Number). The Goal SNR is used to determine how many pulses to integrate over. Once the integration sum reaches the Goal SNR, no more pulses are processed until the next time instant. If the Goal SNR is not attained then the maximum number of pulses is processed [11].

Radar systems can use multiple pulse integration to increase the signal-to-noise ratio. For this radar model a perfect integrator is selected, and in this case the integrated SNR is equal to the number of pulses integrated multiplied by the single pulse SNR. More detail on the pulse integration schemes available in STK can be found in Table 10 of Appendix A.

Filters

Filters are not modelled due to a lack of information and the fact that clutter does not present a significant issue when tracking objects in Space. The radar is also likely to operate at a minimum of a few degrees above the horizon which would negate the effect of ground clutter.

3.3.3 Refraction

Radar analysis in STK uses geometric line of sight (LOS) calculations in the access analysis to determine object visibility. However, refraction can be enabled so that all access computations for the radar are based on the refracted LOS which may enable the radar to see objects over the horizon. The refraction models available in STK provide an estimate of the effects

[3] The algorithm used by STK/Radar for computing probability of detection is from Mitchell, R.L. and J.F. Walker, "Recursive Methods for Computing Detection Probabilities," IEEE Transactions on Aerospace Electronic Systems, Vol. 7, No. 4 (July 1971).

refraction will have on RF signals in the Earth's atmosphere. This impacts the detection ranges from the ground based radar to objects in Space.

For this analysis refraction was enabled when computing access. STK provides three atmospheric refraction models: Effective radius, ITU-R P.834-4 and Satellite Control Facility (SCF), although only the first two were considered in this analysis. Further details of the effective radius method and ITU models can be found in Appendix B and are also described in Blake [12,13].

3.3.4 Constraints

STK/Radar can model various constraints placed on the radar system. This includes a variety of basic generic constraints available to all STK objects, e.g. placing restrictions on the azimuth or elevation of a sensor when computing access.

One restriction placed on the AN/FPQ-14 C-Band radar is the minimum elevation angle, which has been considered in the analysis. In order to negate the effects of ground reflectivity the radar must operate at a minimum of one beamwidth (approximately 0.4°) above the horizon. This is the theoretical minimum elevation that the radar could operate. However, given the location of the radar and expected radiation pattern, the minimum elevation angle that the radar can operate at is likely to be at least 2° to meet radiation safety requirements [1].

3.4 Target Models

Targets[4] are represented in the STK scenario as satellite objects, although it is possible to define other types of objects orbiting the earth such as Space debris and rocket boosters using this object type.

Satellite objects are modelled using the two body propagator and classical (Keplerian) orbital elements. This is an analytical propagator which generates a known solution for the satellite moving around a central body and does not consider other perturbation effects. Four targets are defined for the scenario with circular orbits (apogee equal to perigee) at altitudes of 200, 500, 1000 and 1500 km. An inclination of 98° is used which approximates a sun-synchronous orbit and is commonly used for Earth imaging satellites. The argument of perigee, longitude of ascending node and true anomaly of the orbits are set such that the first pass will be directly over the radar site and the satellite will approach from the north, (Figure 4).

A radar cross section (RCS) is also defined for each target. RCS is a measure of how detectable an object is with radar and is a property of target reflectivity. RCS tends to be related to the size of an object but is also dependent on other factors such as its shape and orientation.

Targets can be assigned a constant RCS value or multiple frequency dependent RCS. For this analysis targets are assigned a single constant RCS value as defined in Table 3. This represents

[4] The term 'target' is used to refer to any vehicle class in STK (e.g. aircraft, ground vehicles, launch vehicles, missiles, satellites and ships) or a ground facility/target class.

an average RCS value for representative target types. This does not accurately reflect the true RCS of objects in Space which are travelling at high velocities and have irregular shapes, e.g. satellites may deploy external sensors, antennas, solar panels etc. which will significantly change the RCS profile. While it is possible to define aspect dependent RCS for objects in STK, this information could not be acquired for the objects considered in this scenario.

Table 3: RCS of Representative Targets in the Scenario

Object Type	**RCS**
Debris	0.01 m^2 (-20 dBsm)
Small Payload	0.1 m^2 (-10 dBsm)
Payload	1 m^2 (0 dBsm)
Booster	40 m^2 (16 dBsm)

4. Scenario

A scenario was developed in STK to assess the detection performance of the radar located at North West Cape, Western Australia for targets with given orbital altitudes, assigned RCS values and minimum SNR required for detection.

The AN/FPQ-14 C-Band radar is modelled as a radar object using the parameters defined in Appendix A. The radar object is attached to a sensor object which in turn is attached to a facility geographically located at Harold Holt. The sensor object is used to enable the radar to track objects assigned for targeting within the scenario. This is referred to as targeted tracking mode in STK. For the purposes of this modelling it is assumed that cueing information, either from another sensor or using orbital element sets in the satellite catalogue, has been provided to the radar for the targets being tracked by the radar in this scenario.

Targets are defined as satellite objects in the scenario for four different orbital altitudes as described in the previous section. Sensor objects are used to visualise the horizon limited ranges from the radar site to the orbital altitudes of the targets, but do not serve any purpose in the analysis.

A screenshot of the STK scenario is shown in Figure 4. This depicts the horizon limited ranges at orbital altitudes of 200 km (yellow), 500 km (blue), 1000 km (green) and 1500 km (red). The satellite targets pass directly over the radar site from the north.

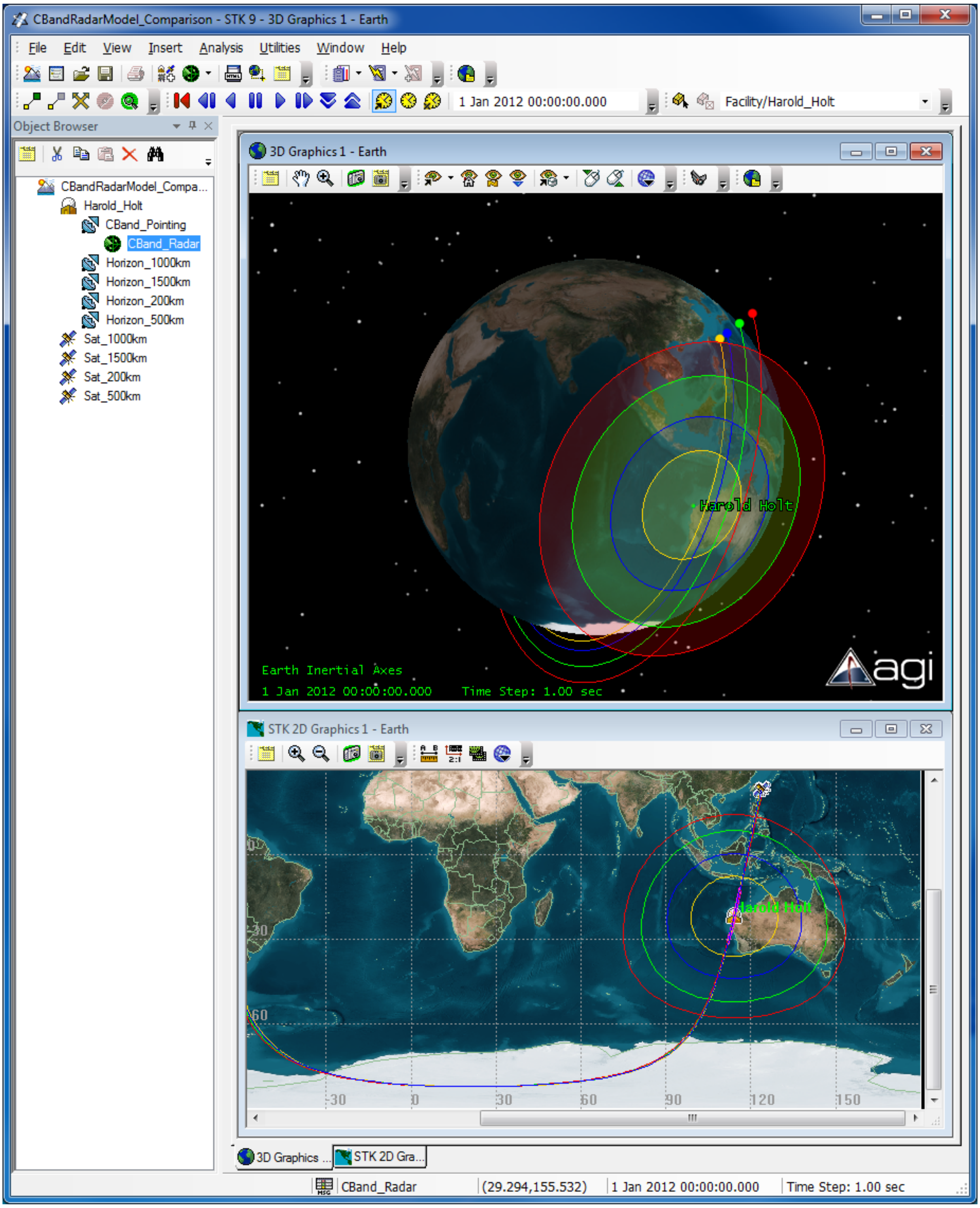

Figure 4: Screenshot of the STK scenario

STK computes access from the radar to a target based on the radar model parameters and constraints placed upon the objects in the scenario. Reports for access from the radar to the target are generated to determine the minimum elevation angle and maximum range for detection. To compute access from the radar to a target of interest, the satellite object

representing that target must be added to the assigned target list in the pointing properties of the tracking sensor the radar object is attached to. For each target type an RCS value is also assigned to that target on the RCS properties page of the satellite object.

A signal to noise ratio (SNR) in the region of 10 to 20 dB was assumed to be required to maintain a track on a target [1]. This constraint is placed on satellite target in the scenario (on the Search/Track constraints properties page) so that azimuth, elevation and range from the radar to the satellite target is only displayed when the integrated SNR exceeds a value set within this range. If this constraint is ignored STK will display access whenever the target object passes within line of sight view of the radar site.

For a given minimum SNR required for detection of 15 dB, which based on previous analysis appears to closely match what was known about the operating performance of the radar, the results showed that orbital objects with a 1 m^2 RCS (considered to be representative of a payload) can be detected out to the radar horizon at an orbital altitude up to about 500 km, whereas detection of much larger objects, e.g. boosters with a 40 m^2 RCS, are horizon limited regardless of the orbital altitude for objects in LEO. Detection of small payload size (0.1 m^2) objects and smaller ones (less than 0.1 m^2) will be limited by the performance of the radar, and debris with an average RCS less than or equal to 0.01 m^2 are unlikely to be detected at the higher LEO altitudes (above about 1200 km).

For this scenario, using the parameters defined in Appendix A and the effective radius method to model refraction, the combinations of RCS values for the representative targets and LEO altitudes with detection ranges that are horizon limited (green), are limited by the performance of the radar (orange) or cannot be detected by the radar (red) are shown in Table 4. The detection ranges will vary depending on the combination of parameters for defining the radar model and targets, and constraints placed upon them in the scenario. If a different refraction model is applied or the effects of refraction were ignored in the analysis this would also changes the detection ranges.

Table 4: Radar detection for different orbital altitude and representative target combinations. Green cells represent horizon limited detection ranges, orange cells represent detection ranges limited by the radar performance and red cells indicate the radar cannot detect the object at the given orbital altitude.

Orbital Altitude	Debris 0.01 m^2 RCS (-20 dBsm)	Small Payload 0.1 m^2 RCS (-10 dBsm)	Payload 1 m^2 RCS (0 dBsm)	Booster 40 m^2 RCS (16 dBsm)
200 km				
500 km				
1000 km				
1500 km				

5. Validation of Results

5.1 Radar Horizon

Ground based observations of objects with an orbital altitude of 500 km and average RCS greater than 1 m^2 (typically a small satellite) are likely to be horizon limited. Larger objects are horizon limited regardless of the orbital altitude within LEO.

For the cases where the detection range is horizon limited, the radar object in the scenario can be replaced with a simple sensor and access computed whenever the target object passes within line of sight of the sensor, i.e. just over the horizon, to compute the maximum range. Similarly a minimum elevation constraint can be applied to determine the maximum range to objects when they pass just above this given elevation from the radar site. This is important for this particular radar, which due to the geographical location (effects of terrain) and radiation safety requirements is likely to be required to operate at a minimum of a few degrees above the horizon.

Refraction also has a significant effect on the detection range from a ground based sensor to objects in Space when observed at very low elevation angles. Since the radar could theoretically operate at a minimum elevation of 0.4°, the effects of refraction needed to be considered in the range calculations.

Using the scenario, the maximum range from the radar to objects at the four representative orbital altitudes of 200, 500, 1000 and 1500 km was computed in STK for minimum elevations at the radar site ranging from 0 to 15°. This was done with refraction disabled, and applying both the effective radius method and ITU refraction models. Details of the refraction model parameters used are given in Table 12-Table 13 of Appendix A.

The STK results with refraction disabled were compared to calculations of the range using ray tracing equations described in Appendix B. The comparison showed excellent agreement between the calculations with only small differences within 5 km, which are likely to be contributed to the detailed Earth orientation model implemented in STK.

Results using the effective radius method for refraction were also computed using STK and an independent implementation of the same method as described in Blake [12,13]. Comparison of the results for the two methods showed differences in the range of up to 3% for the orbital altitude and minimum elevation cases considered in the scenario. At the highest orbital altitude (1500 km) and highest minimum elevation (15°) the results showed almost perfect agreement, however, the effects of refraction at such a high elevation are insignificant. Agreement tended to fall away with increasing altitude and decreasing minimum elevation, with the largest differences occurring for the lowest altitude (200 km) and lowest minimum elevation (0°) case.

Because of the differences observed between the two implementations of the effective radius refraction method, the ITU model of refraction was also validated. Comparisons were made between the ranges computed using the ITU model implemented in STK with those calculated

by numerical integration of equation (14) in Appendix B. Very good agreement was obtained for all cases considered in the scenario. The absolute differences in range were all 7 km or less, and the largest relative difference was 0.6%.

5.2 Radar Range Equation

While the detection ranges of larger objects in LEO are typically horizon limited, objects such as small payloads (e.g. microsats) and debris are not, as was shown in Table 4. For an object with an orbital altitude of 500 km, the minimum RCS for horizon limited performance is about 1 m^2.

The radar range equation was used in previous work [1,9] to estimate the maximum range at which the radar could theoretically detect a particular target. This equation is particularly useful for determining the detection range to smaller targets which are not horizon limited.

A basic form of the radar range equation is:

$$R_{\max} \cong \left[\frac{P_t G_t A_e G_{\text{int}} \sigma}{(4\pi)^2 (S/N)_{\min} k T_S B_N L_S} \right]^{1/4} \tag{5}$$

Where:

P_t – Average transmit power
G_t – Transmit antenna gain
A_e – Receive antenna effective area
G_{int} – Integration gain
σ – Target RCS
$(S/N)_{\min}$ – Min. SNR required for detection
T_S – Radar system noise temperature
B_N – Noise bandwidth
L_S – System losses

The detection range was computed in previous work for different combinations of: orbital altitude of the target; average (single value) RCS of the target; and the integrated SNR required for detection of the target using the technical specifications (Table 1), estimated operating parameters (Table 2) and by making some assumptions about the system losses.

The results from this evaluation of the radar range equation were compared to the detection ranges computed in the STK scenario. An initial comparison of the results from the original work [1] with the STK results using similarly matched parameters (Appendix A), showed differences in the order of 10% (and up to 17%) for the cases considered in the scenario where the detection range is limited by the radar performance and not by the horizon or minimum elevation constraint. In both of these approaches the effective radius method was applied to consider the effects of refraction. However, given the issues with the implementation of this method in STK subsequently discovered, and discussed in the previous section, this may have affected the results contributing to the large differences observed.

Due to the initial poor agreement between the two approaches and following the subsequent acquisition of updated operational information for the radar, a second comparison, with the

effects of refraction ignored, between the results using updated parameters [9] and those computed by STK was undertaken. These results showed very good agreement, with the greatest difference being 4% for the cases considered in the scenario.

A direct comparison could not be made between the two approaches due to differences in some of the parameters used (e.g. antenna beamwidth and gain) and implementation (e.g. the pulse integration method used in the radar modelling in STK). However, the purpose of this comparison was to determine if the STK results were reasonable estimates of the operational performance of the radar for the test cases considered.

For the radar range equation it must also be considered that a +/- 1 dB uncertainty in a system parameter such as the amplifier gain will result in a +/- 6% uncertainty in the detection range [1]. Since the radar range equation is fundamental to the radar performance computed within STK/Radar, it is possible that this may be a contributing factor to the range differences observed given that there were differences in the assumptions and parameters used in the two approaches. Given the limited information available about the radar, both approaches at best only provide a rough estimate of the operational performance of the radar.

6. Conclusion

This report documented the approach used to model the AN/FPQ-14 C-Band radar using the STK software. The approach involved development of a scenario to assess the detection performance of the radar against a satellite target with a given orbital altitude, radar cross section (RCS) value and minimum signal to noise ratio (SNR) required for detection.

This work has contributed to an initial assessment of the operational performance of the radar system against the test cases considered and provided a baseline for conducting more detailed assessments of the capability of this radar and the contribution it could potentially make to surveillance of Space if relocated to North West Cape, Western Australia.

The results showed that for a given minimum SNR required for detection of 15 dB, which based on previous analysis appeared to closely match what was known about the operating performance of the radar, orbital objects with a 1 m^2 RCS (considered to be representative of a payload) can be detected out to the radar horizon at an orbital altitude up to about 500 km, whereas detection of much larger objects, e.g. boosters with a 40 m^2 RCS, are horizon limited regardless of the orbital altitude for objects in LEO. Detection of small payload size (0.1 m^2) objects and smaller ones (less than 0.1 m^2) will be limited by the performance of the radar, and debris with an average RCS less than or equal to 0.01 m^2 are unlikely to be detected at the higher LEO altitudes (above about 1200 km).

It was not possible to completely validate the STK results against those computed using the radar range equation from previous work due to differences in the two approaches, such as different parameters and implementation of methods used. However, comparison of the two

methods indicates that the results obtained from the STK analysis appear to be a reasonable estimate of the operational performance of the radar against the test cases considered.

Validation of the refraction models available within STK was also undertaken as part of this work, given that refraction has a significant effect on the detection range from a ground based sensor to objects in Space when observed at very low elevation angles. The results revealed that the effective radius model, as implemented in STK version 9.2.3, does not produce the same results (for the test cases considered in the scenario) as an implementation of the same method as described in Blake [12,13]. However, the ITU model of refraction in STK matches almost exactly the implementation described in the ITU recommendation [14] and will be applied in future studies when the effects of refraction through the atmosphere need to be considered in STK scenarios.

Due to insufficient information, the target objects considered in the test cases estimated the RCS of the object using a single average representative value. This did not accurately reflect the true RCS of objects in Space which are travelling at high velocities and have irregular shapes that would significantly change the RCS profile.

Future work is anticipated to involve additional analysis using more accurate and detailed information about the radar specifications and operational parameters obtained since this work was originally undertaken. This would enable development of new or refinement of existing models in STK with a higher level of fidelity for assessing the operational performance of the radar. Additional scenarios or targets with aspect dependent RCS profiles could also be developed to further evaluate the performance of the radar.

This work has also demonstrated the capability of STK, which provides a very powerful modelling, simulation and analysis tool and could be used in further studies for assessing the operational performance of other Space surveillance sensors and their potential contribution to the Space surveillance mission.

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Appendix A STK Model Parameters

The parameters defining the STK object models of the AN/FPQ-14 C-Band radar and satellite targets in the scenario are presented here. Not all parameters for STK objects or the STK/Radar settings are listed and it is assumed that the default values have been accepted in these instances or are not applicable. The tables presented contain details and descriptions of the parameters from the information contained within the relevant sections of the STK 9.2 Desktop Application Help [7].

A.1 Radar: Basic System Definition

The radar operating parameters (Table 5), antenna parameters (Table 6) and system temperature (Table 7) presented here are defined in the radar object properties under the Basic → System page.

Table 5: Radar Operating Parameters

Parameter	**Description**	**Value/Setting**
Operation	The operating mode of the radar. Options are: **Monostatic** (a common antenna is used for both transmitting and receiving); or **Bistatic** (the transmit and receive antennas are not co-located)	Monostatic
Frequency/ Wavelength	Frequency or wavelength of the radar (defined for monostatic operation only)	5.65 GHz (mid range frequency)
Peak Power	Peak output power of the transmitter (defined for monostatic operation only)	2.5 MW (63.98 dBW)
Bistatic transmitter	The transmitter radar in a bistatic radar system (defined for bistatic operation only)	n/a

For this model the antenna size is set to 29 ft (8.8392 m), which gives a computed beamwidth of 0.354° and gain of 51.779 dB, both of which are slightly less than the estimated operating parameters in Table 1.

The STK default values were used for both the antenna efficiency (55%) and backlobe gain (-30 dB) in the absence of information on these parameters being available for the radar. Varying the backlobe gain of the antenna did not impact the detection ranges computed in the scenario.

Changing the antenna efficiency will also change the antenna gain. In order to match the gain with the value listed in Table 1 (53 dB), the efficiency would need to be set to 72.9%, which is at the high end for this antenna type where the efficiency is typically between 50 and 75%.

Since the parameters for the diameter, beamwidth and gain are explicitly specified for the radar it is not possible to replicate these within the STK model given the way in which it is implemented.

Table 6: Antenna Parameters

Parameter	Description	Value / Setting
Diameter	Diameter of the dish	29 ft (8.84 m)
Beamwidth	Antenna beamwidth	0.354 deg (calculated)
Gain	Maximum gain	51.779 dB (calculated)
Frequency used for calculations	The frequency specified in the radar operating parameters	5.65 GHz
Antenna Efficiency	The efficiency factor of the dish (degradation in performance)	55%
Backlobe Gain	The gain of the antenna outside the main lobe beamwidth	-30 dB

The estimated operating characteristics of the radar assume a typical noise figure of 3 dB at 290 K, giving an estimated system noise temperature of 578.6 K. This was estimated by multiplying the ambient temperature by the receiver noise figure [1]. The system temperature parameters are shown in Table 7. Here STK computes a system noise temperature of 578.6 K for a noise figure of 3 dB and antenna noise temperature of 290 K.

Table 7: System Temperature

Parameter	Description	Value / Setting
System Temperature	The inherent noise characteristics of the system. Available options are: 'Constant' (and enter a value directly) or 'Calculate' (based on the parameters entered below)	Calculate: 578.6 K
Receiver Noise Figure	The contribution to the total system noise by the gain stages of the receiver	3 dB
Transmission Line Loss	The loss of the transmission line between the antenna and receiver	0 dB
Transmission Line Temp	The physical temperature of the receiver transmission line	290 K

Parameter	Description	Value / Setting
Antenna Noise	Noise that the antenna picks up from radiating bodies within its radiation pattern. Available options are: 'Constant' (and enter a value directly) or 'Calculate' by selecting to use: Earth, Sun, Atmosphere, Rain, Clouds & Fog, Tropo Scintillation, and/or Cosmic Background noise in the calculation	Constant: 290K
Earth Temperature	The Earth temperature at the local receiver/radar level	N/A

A.2 Radar: Search/Track Mode

The Search/Track mode parameters of the radar including the fixed PRF mode (Table 8), probability of detection (Table 9), pulse integration mode (Table 10) and pulse integration method (Table 11) presented here are defined in the radar object properties under the Basic → Search/Track page. The fixed PRF mode parameters in Table 8 are derived using the maximum values of PRF and pulse width from the radar specifications.

Table 8: Fixed PRF Mode Parameters

Parameter	Value / Setting
Pulse Repetition Frequency	640 Hz
Unambiguous Range	234 km (calculated)
Unambiguous Velocity	8.5 m/s (calculated)
Pulse Width	12.5 μs
Duty Factor	0.008 (calculated)

Table 9: Probability of Detection

Parameter	Description	Value / Setting
Probability of False Alarm	The probability that a target is declared to be present when none exists. Value in the range of 0-1	10^{-4} (STK default)
CFAR Reference Cells	Number of reference cells around the cell being examined for the presence of a target. This parameter is optional. If selected, the user enters the desired integer value	Not selected

Table 10: Pulse Integration Mode

Parameter	Description	Value / Setting
Analysis Mode	For a Fixed PRF radar, the user can select either an integration analysis based on the desired signal-to-noise ratio (**Goal SNR**), or a fixed number of pulses (**Fixed Pulse Number**). For a Continuous Wave system, the choice is between **Goal SNR** and **Fixed Time**.	Goal SNR, with the SNR in the range of 10 – 20 dB
Maximum Pulses	Available only when the search/track mode is **Fixed PRF** and the integration analysis mode is **Goal SNR**. The user enters the desired value for maximum pulses	Dependent on desired SNR. For a goal SNR of 15 dB, the maximum number of pulses was set to 40. More details can be found in [1, Table 11].

For the pulse integration method, one of the options in Table 11 is selected and the desired value for ρ (if applicable) specified. Alternatively, an integration gain file that specifies the integration gain for a given number of pulses integrated can be used.

Table 11: Pulse Integration Method

Parameter	Description	Value / Setting
Perfect Integrator	If M is the number of pulses integrated, SNR_1 is the per pulse SNR, and SNR_M is the integrated SNR, $SNR_M = M\ SNR_1$.	Selected
Constant Efficiency	If M is the number of pulses integrated, SNR_1 is the per pulse SNR, and SNR_M is the integrated SNR, $SNR_M = \rho M\ SNR_1$, where $0.0<\rho<1.0$. Not available for CW radar.	Not Selected
Exponent on Pulse Number	If M is the number of pulses integrated, SNR_1 is the per pulse SNR, and SNR_M is the integrated SNR, $SNR_M = M\ \rho\ SNR_1$, where $0.0< \rho <1.0$. Not available for CW radar.	Not Selected
Integration Gain File	Use an Integration Gain File. Not available for CW radar or Fixed Pulse Number integration mode	N/A

A.3 Target: Refraction

The refraction parameters using the Effective Radius Method and IRU model are shown in Table 12-Table 13. These properties are set for each satellite object on the Basic → Refraction properties page.

Table 12: Refraction Parameters for the Effective Radius Method

Parameter	Description	Value / Setting
Effective Radius Factor	The multiplicative factor that scales the Earth's size in the model	1.3333
Refraction Ceiling	The maximum altitude of the lower object for which the refraction angle will be computed	5 km
Max Target Altitude	For objects at higher altitudes (e.g. satellites), the refraction angle computed by the effective radius model is a poor approximation to reality (because the refraction angle is too large). If the higher object's altitude is above the maximum target altitude, then the effective radius model does not apply	10 km
Extrapolate Above Max Altitude	If extrapolation is enabled, then the refraction angle will still be computed when the higher object exceeds the maximum target altitude using a modified approach	Enabled

Table 13: Refraction Parameters for the ITU-R P.834-4 model

Parameter	Description	Value / Setting
Refraction Ceiling	The maximum altitude of the lower object for which the refraction angle will be computed	5 km
Atmospheric Altitude	The maximum altitude of the knee point	10 km
Knee Bend Factor	The factor used in computing the approximate location of the knee point	0.2

A.4 Target: RCS

The parameters in Table 14 are defined for assigning RCS bands to a target. These parameters are set for each satellite objects on the RF → RCS properties page.

Table 14: Target RCS Properties

Parameter	Description	Value
Min	The minimum frequency in the range	3 MHz
Max	The maximum frequency in the range	300 GHz
Mode	The choices are Constant RCS or an Aspect Dependent RCS File	Constant RCS
Swerling	To account for RCS fluctuations, STK/Radar uses a set of fluctuation models developed by Swerling. Case 0 assumes no fluctuation. Cases I and III assume that fluctuations are correlated during a scan but uncorrelated from one scan to the next. In Cases II and IV, fluctuations are more rapid and are assumed to be uncorrelated from pulse to pulse	Case 0 (No fluctuation)
Value	The RCS value	Dependent on object (see Table 3)

Appendix B Refraction Modelling

The radar horizon lies beyond the visual horizon, due to refraction in the atmosphere. At microwave frequencies only refraction in the troposphere needs to be considered. The troposphere is the non-ionised part of the atmosphere which extends from the Earth's surface up to an altitude of about 10 km. Refraction is caused by a variation in the refractive index n. It can be modelled by ray tracing [12, Chapter 5]. Snell's law is the basis of ray tracing theory. If ψ is the angle between the ray and the refractive index gradient, then according to Snell's law $n \sin \psi$ is constant, provided the direction of the refractive index gradient is constant. If refractive index gradient in the atmosphere is assumed vertical and the Earth is regarded as a perfect sphere, the atmosphere is then spherically symmetric. In spherical coordinates Snell's law takes the form $n\, r \sin \psi = C$, where r is the radial distance from the centre of the earth to a point on the ray and C is a constant. It can also be expressed in terms of the local elevation angle of the ray θ, which is the complement of ψ, as $n\, r \cos \theta = C$. If n_0, r_0 and θ_0 are the values of n, r and θ at the initial point of the ray,

$$nr \cos\theta = n_0 r_0 \cos\theta_0 \tag{6}$$

Since $r = r_0 + h$,

$$\cos\theta = \frac{n_0 \cos\theta_0}{n(h)\left(1 + h/r_0\right)} \tag{7}$$

Figure 5 shows the geometry for ray tracing in a spherically symmetric atmosphere. Figure 6 shows a differential element of the ray path. From this figure it can be seen that

$$\sin\theta = \sqrt{1 - \cos^2\theta} = \frac{dh}{ds} \tag{8}$$

Thus

$$ds = \frac{dh}{\sqrt{1 - \cos^2\theta}} \tag{9}$$

The increment ds is the physical distance along the ray path. This must be multiplied by the refractive index to get the increment in the measured radar range R, i.e. $dR = n\, ds$. Substituting equations (7) and (9) gives the ray tracing integral for the range:

$$R\left(h_1, \theta_0\right) = \int_0^{s(h_1)} n\, ds = \int_0^{h_1} \frac{n(h)\, dh}{\sqrt{1 - \left(\dfrac{n_0 \cos\theta_0}{n(h)\left(1 + h/r_0\right)}\right)^2}} \tag{10}$$

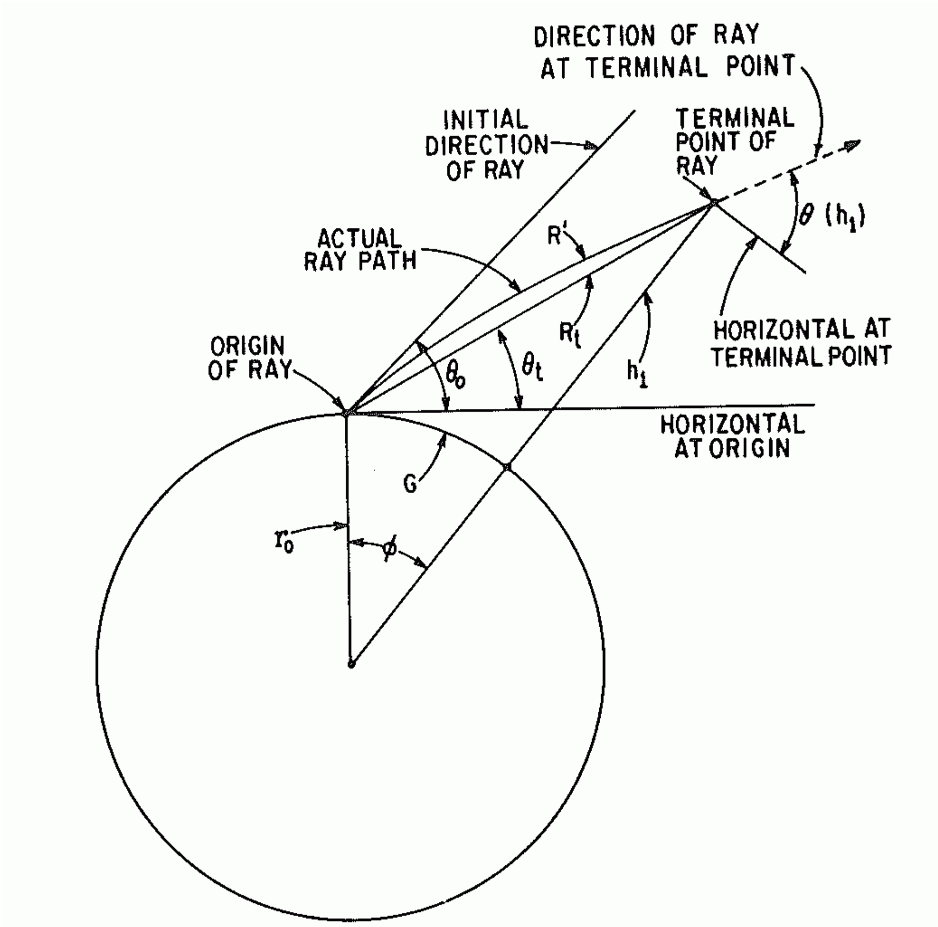

Figure 5: Ray tracing geometry for a spherically symmetric atmosphere. Reproduced from Figure 5-1 of [12].

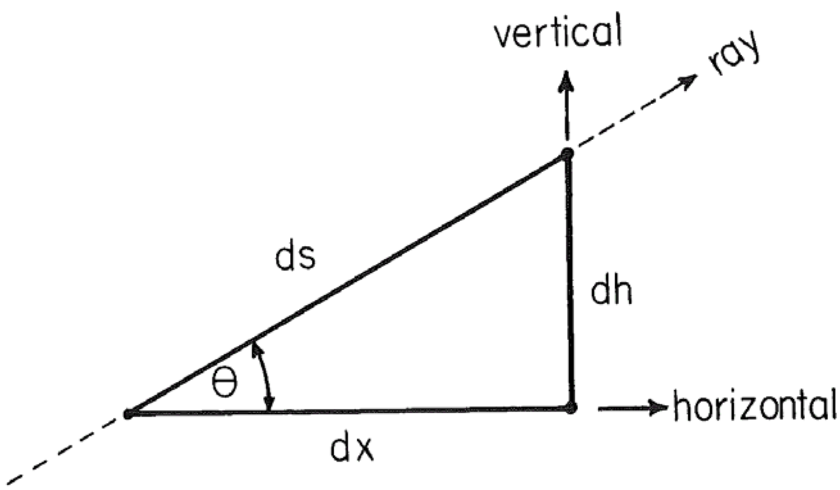

Figure 6: Differential element of the ray path. Reproduced from Figure 5-2 of [12].

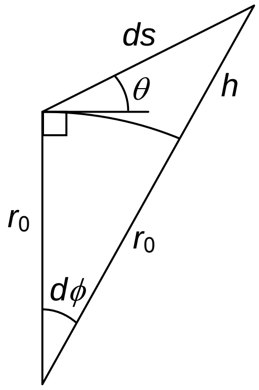

Figure 7: Differential elements used to calculate the ground range.

The ground range is $G = r_0\phi$. From the triangle in Figure 7 we have

$$\frac{h+r_0}{\cos\theta} = \frac{ds}{\sin(d\phi)} = \frac{ds}{d\phi} \tag{11}$$

Hence

$$r_0 d\phi = \frac{r_0}{r_0+h}\cos\theta ds \tag{12}$$

Substituting equations (7) and (9) gives

$$r_0 d\phi = \frac{dh}{\left(1+h/r_0\right)\sqrt{\left(\frac{n(h)\left(1+h/r_0\right)}{n_0\cos\theta_0}\right)^2 - 1}} \tag{13}$$

The integral for the ground range is [13]

$$G\left(h_1,\theta_0\right) = \int_0^{\phi(h_1)} r_0 d\phi = \int_0^{h_1} \frac{dh}{\left(1+h/r_0\right)\sqrt{\left(\frac{n(h)\left(1+h/r_0\right)}{n_0\cos\theta_0}\right)^2 - 1}} \tag{14}$$

Ray tracing in a stratified atmosphere amounts to the evaluation of the integral (10) or (14) with an assumed refractive index profile $n(h)$. If the refractive index gradient is assumed constant, so that $n(h)$ is linear, the integral can be solved analytically. This is a useful approximation, which leads to the effective radius model for refraction. A more realistic model is the exponential profile

$$n(h) = 1+\left(n_0-1\right)e^{-ch} \tag{15}$$

c is a constant related to the refractive index gradient at the surface. The ray tracing integral must be evaluated numerically, but this is straight forward using standard quadrature routines. The ray tracing integrals (10) and (14) both have a singularity at $h = 0$ for $\theta_0 = 0$. Reference [13] provides alternate forms of these integrals which are better suited to numerical computation. If the radar is observing a target in Space, the integration can be stopped at around 50 km altitude, where the refractive index differs from 1 by less than 10^{-6}. The remainder of the ray path is calculated from geometry, using equation (7) to determine the elevation angle at 50 km altitude.

The International Telecommunications Union (ITU) recommendation on the effects of tropospheric refraction [14] contains a refractive index profile in the form (15), with the global average values $n_0 = 1.000315$ and $c = 0.1361$. The ITU model in STK is based on this recommendation. Rather than calculating the range, it makes use of a polynomial formula for the apparent elevation (equations 13 and 14 in [14]) to calculate access.

The ITU model implemented in STK has been compared with ground ranges calculated by numerical integration of equation (14). The comparison was made for satellites in circular orbits at altitudes of 200, 500, 1000 and 1500 km with sensor elevation angles θ ranging from 0 to 15°. Very good agreement was obtained. The absolute differences in range were all 7 km or less, and the largest relative difference was 0.6%.

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19. ABSTRACT

A model of the AN/FPQ-14 C-Band radar was developed using Analytical Graphics, Inc. (AGI) STK software to support studies investigating the operational performance of the system for surveillance of Space and the contribution it could make to the Space situational awareness mission. STK scenarios were developed to assess the detection performance of the radar model against a satellite target with a given orbital altitude, radar cross section (RCS) and minimum signal to noise ratio (SNR) required for detection. These results were compared to those obtained by evaluating the radar range equation. A comparison was also made on the effects of refraction using the effective radius method and International Telecommincations Union (ITU) model.

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